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WAKE INTERACTION EFFECTS ON THE TRANSITION PROCESS ON TURBINE BLADES

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ABSTRACT

The unsteady behavior of a 2-D gas turbine rotor blade boundary layer was observed using wide bandwidth surface heat transfer thin film gauges. The tests were conducted in a compression heated short duration wind tunnel cascade at realistic gas turbine aero/thermodynamic conditions. Wake passing effects were generated using a rotating set of bars upstream of the airfoil. The unsteadiness of the wake and shock interactions was observed through the effects on surface heat transfer. The unsteadiness of natural transition of the boundary layer was also observed. Heat transfer enhancement by the wake passing was observed along with the convection rate of the wake through the passage. This was compared with an inviscid time-marching prediction. The growth and convection of turbulent spots were also observed and compared with a numerical turbulent spot model. Quantitative information on intermittency and mean spot convection rates were obtained for the first time in realisitic gas turbine flow conditions. Comparisons were made between transitional behavior of the boundary layer with and without wake disturbances present. Supporting tests were conducted on wake characteristics in transonic flow and on wake-disturbed heat transfer to a 3-D rotating annular turbine rotor stage.

INTRODUCTION

The design of efficient, high-specific power gas turbine engines depends in an important way on a fundamental understanding of the aerodynamics and related heat transfer in the hot section stator and rotor blades. An important area of researc' 'n this area involves trying to better understand unsteady phen[illegible]on such as wake interaction effects and the transition process between laminar and turbulent boundary layers along the blade surface.

The work discussed in this report involves experiments and analysis centered around a typical turbine blade aerofoil in a 2-D cascade transient heated wind tunnel. Free stream unsteadiness was provided by upstream grids and rotating cylindrical bars. The measurements were primarily confined to instantaneous surface heat transfer. Flow unsteadiness associated with transitional boundary layers and wake-passing events could thus be tracked with some precision. Supporting

tests were conducted to characterize the wakes of cylinders in transonic flow and to extend the 2-D cascade environment to an annular 3-D rotating single stage environment.

EXPERIMENTAL SET-UP

The main experimental facility used was the Oxford University Isentropic Light Piston Tunnel (ILPT) with 2-D cascade test section, (Figure 1). The facility and instrumentation techniques have been described in the literature e.g., Refs 1, 2, and 3. The techniques used for simulating wake-passing events in the 2D cascade were described by Doorly and Oldfield (Ref. 4). The basic (and unique) instrumentation which permitted the resolution of very high frequency transient events such as wake passing and transition was thin film surface temperature thermometers and fast multi-channel (16) transient recorders. This technique, developed by M.L.G. Oldfield and his students, was capable of providing instantaneous surface heat transfer rate signals at bandwidths approaching 100KHZ. Supporting measurements on wake characteristics were also made in a 9" x 3" transonic/supersonic flow wind tunnel and in an annular, rotating single stage turbine attached to the ILPT.

RESULTS

a) Wake Interaction Effects in 2-D Cascades

The primary results of simulated wake interaction effects in the 2-D cascade aerofoils are summarized in the publications of the work e.g., Refs, 5, 6, 7, 8 and 9. Individual wakes could be easily detected and tracked. Quantitative information extracted included, 1) the absolute level of heat transfer during the transient event, 2) the apparent tracking speed of the wake along the blade surface and 3) details of the wake structure through ensemble averaging of many single events. One important finding was that the leading edge of the turbulent patch associated with wake passing propagated at near the free stream velocity whereas the trailing edge eventually settled into a propagation velocity of near 0.5 times the free stream value (Figure 2). There is some evidence that while the presence of the wake at the edge of the boundary layer is immediately manifest in an increase in the heat transfer rate to the surface, there is a short delay before the

induced patch of turbulence takes on a propagation velocity characteristic of self-sustained turbulent spots. Much work remains to be done to clarify this.

b) Transitional Boundary Layers 2-D Cascade

The primary results of the transition measurements have been reported in the literature (Refs. 6, 7, 8, 9, and 10). The main findings show clearly resolved transient excursions in heat transfer which are consistent in every way with the formation, propagation, growth and eventual merger of turbulent spots arising out of an initially laminar boundary layer (Figure 3). The laminar levels were determined from tests at low free stream turbulence. The 100KHZ multi-channel simultaneous tracking of rapid excursions in the absolute levels of surface heat transfer rates allowed quantative information to be extracted from the transitional data. This included the specification of the spot propagation velocities along the blade surface (Figure 4) and also the distribution of fraction of time that the flow at any location is turbulent (the intermittency) (Figure 5). Mean propagation velocities were consistent with much low speed data. This new data represents the first reported spot convection rate data at transonic conditions and at otherwise simulated turbine engine conditions. Quantified intermittency data is also central to the code development work which is an important tool for the turbine designer. The location and extent of the transition zone must be modelled accurately for the heat transfer and loss estimates to be realistic.

c) Wake Effects and Transition 2-D Cascade

Tests were done on transitional boundary layers with and without wakes sweeping over the blade surface. The wake generator was run with only two bars thus leaving a relatively long period of quiet flow between wakes. Typical results are shown on the left-hand side of Figure 6 where only one wake is shown for clarity. Qualitively, the transition process proceeds at the same rate and over the same range as it did on the undisturbed boundary layer and shown in more detail in Reference 7 and 8. There was not enough detail to do a quantitative statistical evaluation of the intermittency, but the pattern is remarkably similar. In other words, although the transition is nearly immediately forced to turbulence under the passing wake, the

"natural" transition in the boundary layer just outside the wake proceeds as if the wake was not present.

d) Numerical Predictions of Wakes

The first part of the numerical modelling effort concentrated on predicting the path the rotating bar wake was expected to take as it encountered the blade row and progressed through the passage.

A two-dimensional model was assumed using conditions at bar mid-point. The procedure followed that described by Doorly (Ref. 12) known as a "striped air" calculation and which has now been automated. This also allows for a spreading wake width being proportional to the square-root of the distance from the bar along the line of U_{rel} with the constant of proportionality derived from a data base of wake measurements. The wake is then convected through the blade row passage using an inviscid time marching flow field calculation. From an initial position, elements of the wake are convected by small time steps using the local velocity interpolated from the predictions until the bar reaches the specified location. The differential velocities in the flow field cause distortions of the wake along its length and across its width as it is accelerated through the passage. The results of such a calculation are shown in Figure 7. The position of the wake calculated by this method agrees well with the positions shown at the same time on schlieren photographs presented by Schultz et al. (Ref. 6).

It was then possible to compare the wake passage prediction from the time marching (striped air calculation) scheme with the observed suction surface heat transfer record. It should be emphasized again that the prediction for the wake passage is based on an inviscid flow field calculation whereas the observed heat transfer effects are measured on the blade surface, at the base of the blade viscous boundary layer. The results are shown in Figure 2 given predicted and observed wake path for the leading and trailing edge as a trajectory in an x-t diagram. The figure shows excellent agreement for the leading edge prediction with an expected difference in trailing edge prediction. Also shown on Figure 8 are predicted propagation trajectories for the leading and trailing edge of the wakes based simply on a range of assumed fractions of actual local free stream velocities. The values of $0.88U_\infty$ and $0.5U_\infty$ were selected from values

commonly accepted for turbulent spot leading and trailing edge propagation rates.

e) Numerical Prediction of Transition

A generalized model time-marching scheme was developed (see Ashworth, Ref. 9) for the prediction of transitional intermittency using the turbulent spot model proposed by Emmons. This model allowed for turbulent spots to be generated randomly at any point on the blade surface and subsequently propagated downstream at an arbitrary growth angle and leading edge and trailing edge propagation rate (as a fraction of free stream velocity). The self-similar spot growth characteristics were then combined with the blade geometry information and thin film sensor locations to predict the fraction of time the spots contact with the films (or part thereof). This would then give predictions of intermittency consistent with what would be measured with the sensing elements in these experiments.

A typical plan view of the model surface (with sensing elements in place) showing the coverage of turbulent spots generated by the above procedure is shown in Figure 8 for a frozen instant of time. In this way an effective intermittency can be estimated by summing the portion of the gauge covered by turbulence (either from a wake or a spot). Intermittency values can then be easily converted to Nusselt number values by summing the contributions of laminar Nusselt number and turbulent Nusselt number for each gauge. This results in heat transfer predictions such as shown in Figure 6. This clearly shows the similarity between the data presented and the prediction method.

f) Bar Wakes in Transonic Flow

In order to understand fully the relationship between two dimensional testing for transition behaviour in boundary layers and the equivalent experiments in a three dimensional fully rotating stage experiment, it is necessary to understand the differences between these two experiments as well as their similarities, in areas of relevance to boundary layer behaviour.

In the final year of the grant, Izsak (Ref. 11) conducted a program of work aimed at studying wakes and transition in a rotating stage. The

key work concerned the detailed study of wakes generated by the rotating bar generator for both velocity deficit, turbulence spectra, and comparison with theoretical profile. In addition a considerable amount of schlieren flow visualisation work was carried out which revealed interesting and surprising characteristics of the wake generated from a bar as the flow Mach number increases.

Izsak found good agreement between predicted wake velocity deficit with position across the wake both in terms of hot wire anemometer measurements (Figure 9), and as far as new data is concerned, saw peaks in unsteadiness at the edges of the wake both in terms of hot wire anemometer measurements (Figure 10) and measurements made with a fast response semiconductor pressure probe (Figure 11). A schlieren flow visualisation of the wake at a flow Mach number of .93 found that as the Mach number was increased the shock structure moved to a more oblique angle causing a contraction of the wake, which ultimately resulted in a narrowing of its width and a reduction of its foot-print. This, ultimately, could be the explanation of the reduced effect of the wake in the work of Ashworth et al in cascade, in comparison with Doorly.

g) Wake Effects in 3-D Annular Stage

This characterization of the wake led to a prediction of its form in the fully rotating experiment. In the data set available it is still too small to permit much transition analysis. The agreement between 2D and 3D time mean heat transfer is encouraging at this early stage.

As more data is acquired, it is hoped to understand further the role of the shock-wake activity and its relation to transition behaviour in the rotating stage.

CONCLUSIONS

It was shown that wide-bandwidth heat transfer instrumentation was able to track trajectories of both unsteady wake passing events and transitional turbulent spots on a turbine airfoil under a simulated gas turbine environment. The observed behavior was accurately modeled by a time-marching simulation of both the inviscid wake passing interaction and the random generation and growth of turbulent spots

based on the well established low speed theory and observations of the final 3-D stages of boundary layer transition. Detailed mean and instantaneous surface heat-transfer measurements in transitional boundary layers were presented. Mean heat transfer leveis at laminar and turbulent conditions compared well with standard prediction methods. Detailed measurements of turbulent spot growth, convection rate and merger were presented. Quantitative comparisons with intermittency data was made using a model based on Emmons' turbulent spots. A new transition simulation technique was developed allowing comparison with the unsteady transitional heat transfer data.

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Summary of Grant Publications

Ashworth, D.A., J.E. LaGraff, D.L. Schultz, and K. Grindrod, "*Unsteady Aerodynamics and Heat Transfer Processes in a Transonic Turbine Stage*," J. Eng. for Gas Turbines and Power, Vol. 107, pp. 1022-1030, 1985.

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Ainsworth, R.W., Schultz, D.L., Davies, M.R.V., Forth, C.J.P., Oldfield, M.L.G., Hilditch, M.A., Sheard, A.G., "Transient Facility for the Study of the Thermofluid-dynamics of a Full Stage Turbine Under Engine Representative Conditions," ASME International Gas Turbine and Aero-engine Congress, June 1988, 88-GT-XX.

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Izsak, M.J., "*Wakes and Transition in a Rotating Gas Turbine Stage*," MSc. Thesis, Oxford University, 1988.

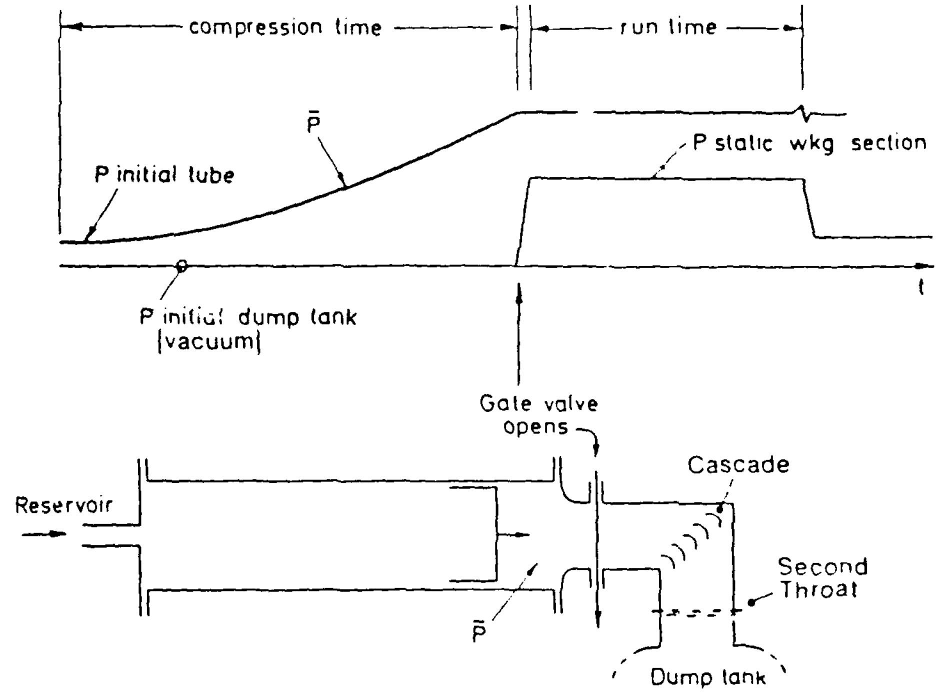

FIG. 1 Schematic of Isentropic Light Piston Tunnel

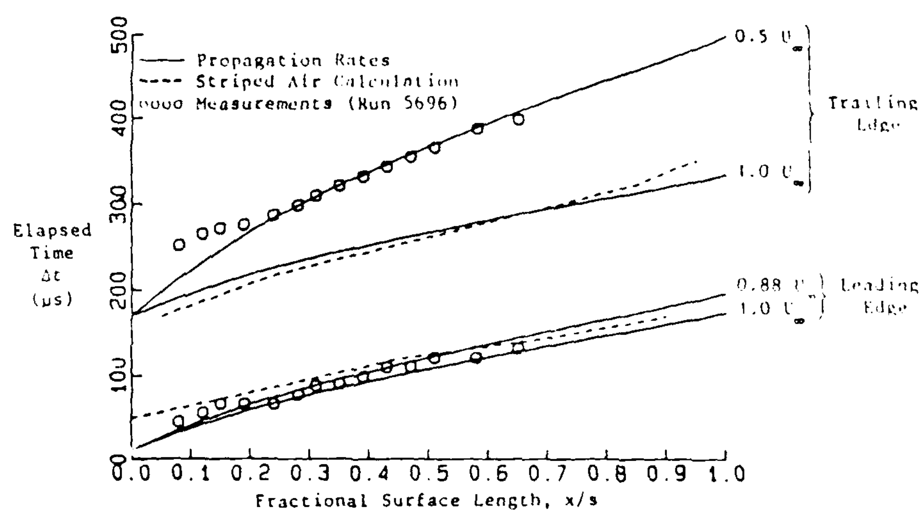

Fig. 2 - Comparison of measured leading and trailing edges of a wake-induced turbulent patch with prediction.

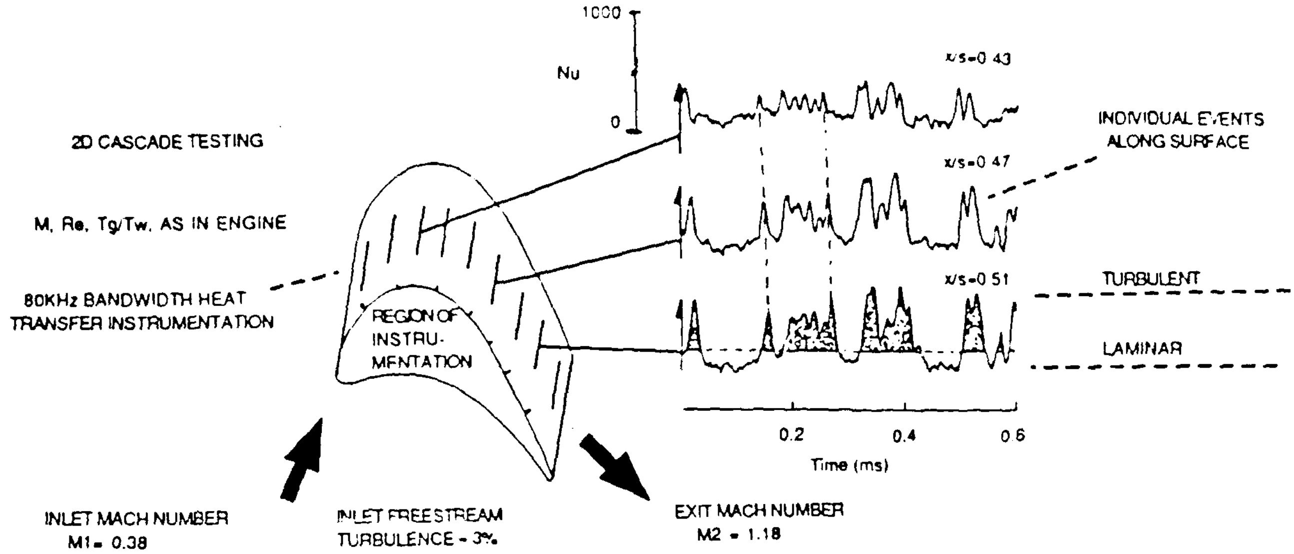

Fig.3 Time resolved surface heat transfer rates on successive gauge positions showing convection rate and intermittency estimation procedure.

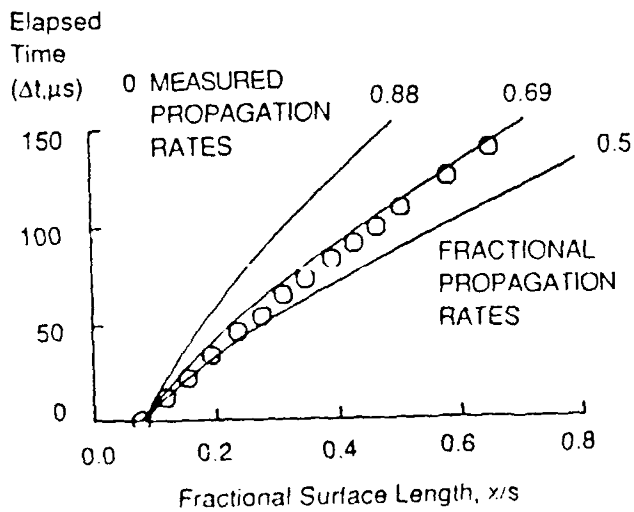

Fig. 4 Turbulent spot trajectories along model surface.

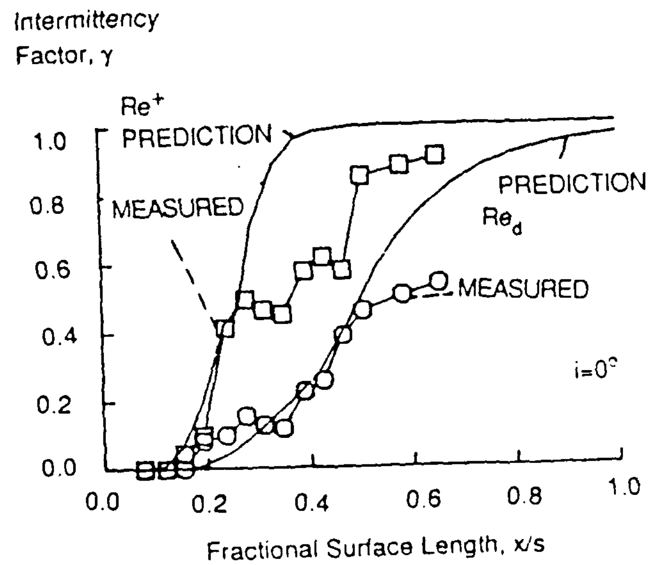

Fig. 5 Measured intermittency distribution and prediction.

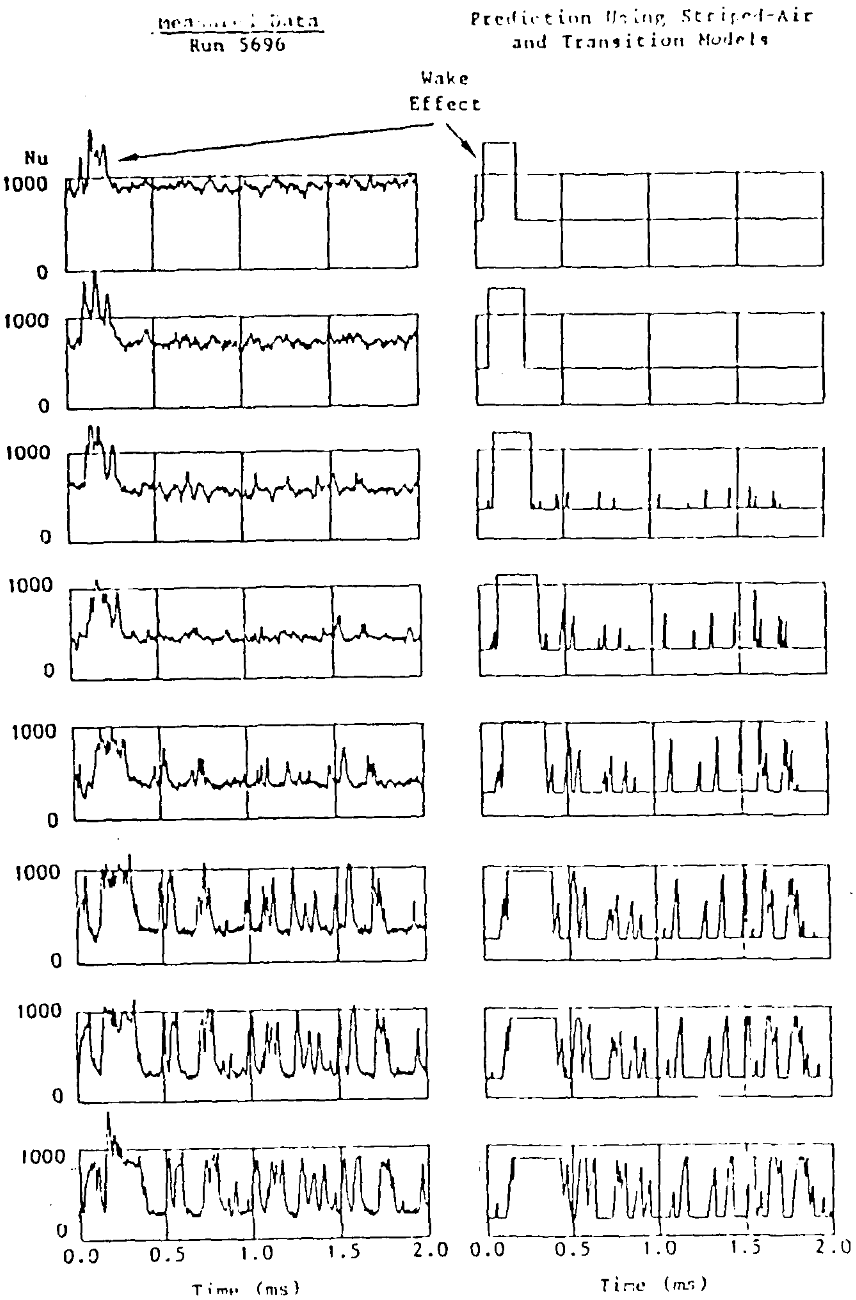

Fig. 6 · Comparison of the measured and simulated instantaneous heat transfer on the model surface with wake-passing and transition.

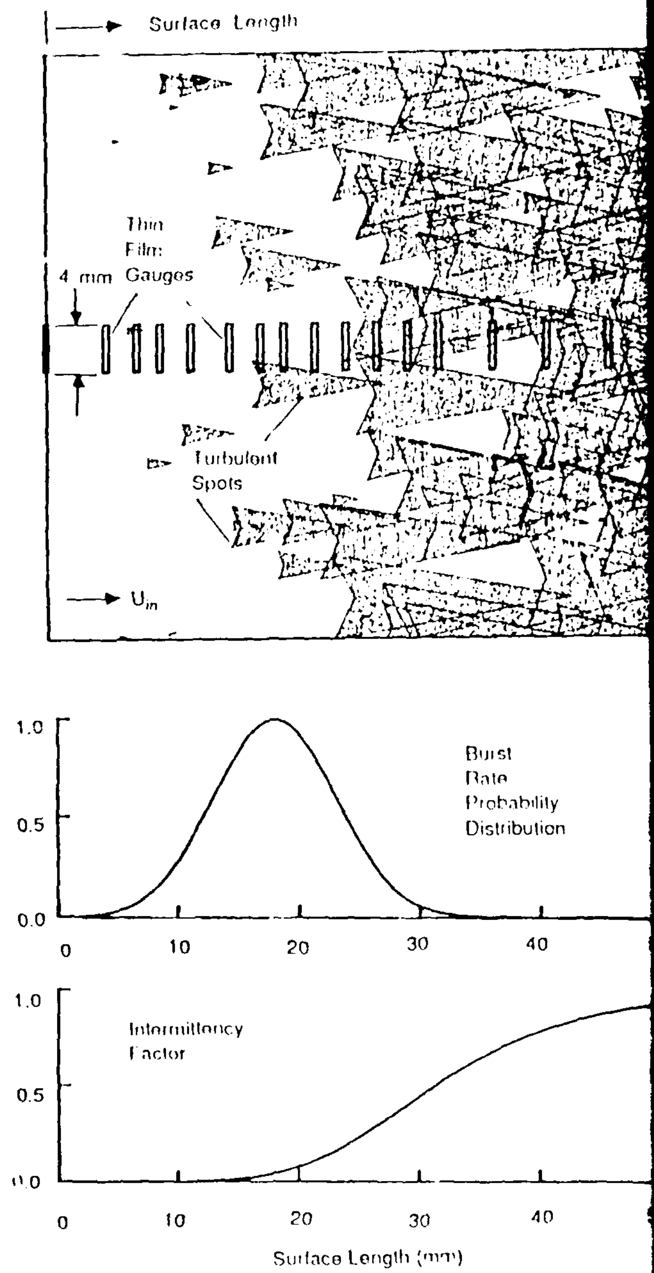

Fig. 8 Plan view of simulation of transition on model surface with assumed burst rate distribution and resulting intermittency.

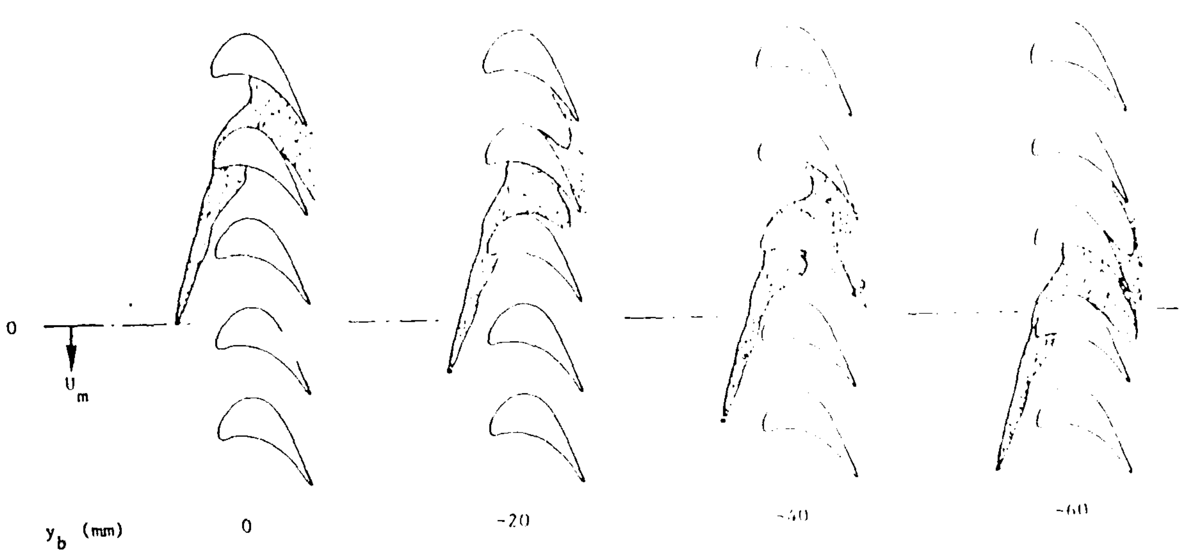

Fig. 7 - Striped-air calculation for four positions of the bar.

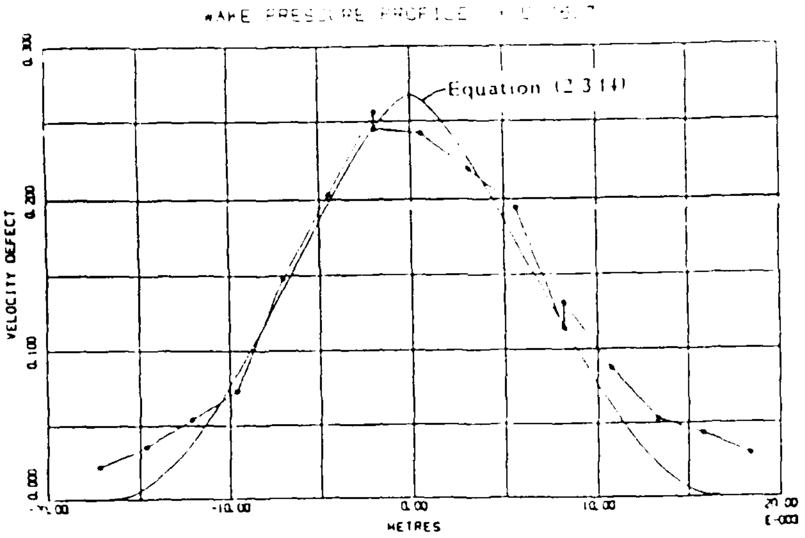

Fig. 9 Bar Wake Velocity Defect and Prediction M=0.94 x/d=26.7

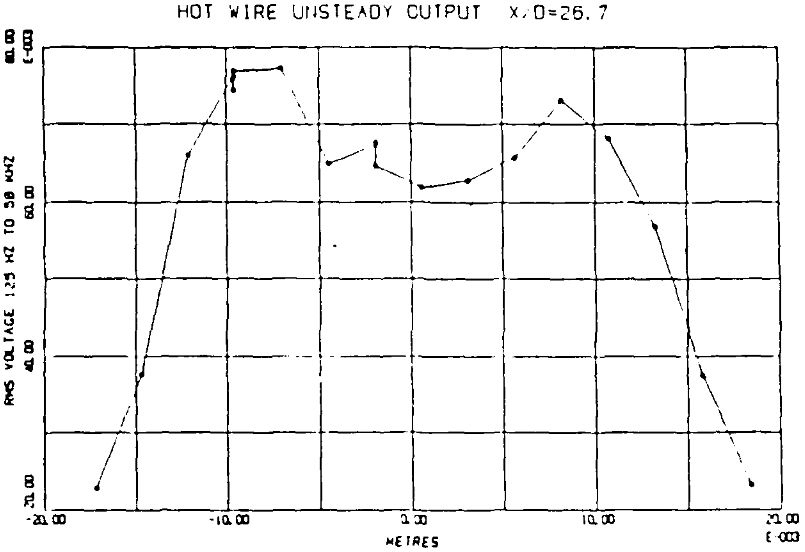

Fig. 10 Hot Wire RMS Voltage Distribution M=0.94 x/d=26.7

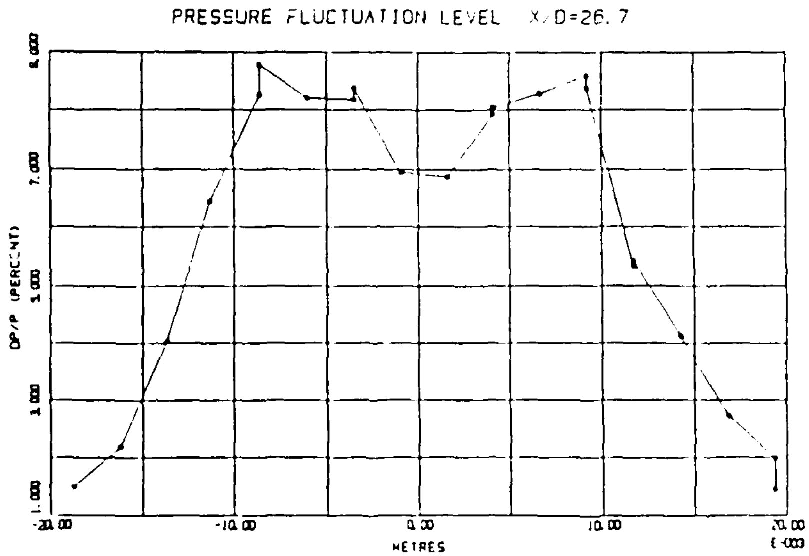

Fig. 11 Pressure Fluctuation Distribution M=0.94 x/d=26.7